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PROPERTIES OF ULTRA-HIGH STRENGTH BAINITIC STRUCTURES

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FOREWORD

This report was prepared by Armour Research Foundation of Illinois Institute of Technology under USAF Contract No. AF 33(657)-8426. This contract was initiated under Project No. 7351, "Metallic Materials," Task No. 735105, "High Strength Metallic Materials." The work was administered under the direction of the Metals and Ceramics Division, Air Force Materials Laboratory, Deputy Commander/Research and Engineering, Aeronautical Systems Division, with Lt. F. L. Krempski acting as project engineer.

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Personnel at Armour Research Foundation who made major contributions to this program were C. R. Simcoe and J. P. Sheehan. The data reported are recorded in ARF Logbooks C-12778 and C-13283. The report is identified internally as ARF-B240-11.

ABSTRACT

The tensile properties and fracture toughness were measured in sheet material for isothermally transformed lower bainite and tempered martensite in a series of alloy steels. The major experimental variables were transformation temperature, tempering temperature, carbon content, and alloy additions.

Carbon contents of 0.55 to 0.60% or higher are required to develop ultra-high strength levels in lower bainite. Lower bainite with yield strengths above 220,000 psi had slightly to moderately lower fracture toughness than tempered martensite in typical low alloy steels at comparable yield strengths. At yield strengths below 220,000 psi, lower bainite was equal to or slightly better than tempered martensite in typical low alloy steels, except the 1Cr-1Mo composition which is superior to the other alloy steels studied at yield strengths up to 240,000 psi.

The fracture toughness of lower bainite is discussed in terms of transformation temperature, M_s temperature, and steel composition. A 9Ni-4Co steel developed an atypical bainitic microstructure at transformation temperatures just above the M_s temperature.

This technical documentary report has been reviewed and is approved.

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I. INTRODUCTION

There is continuing interest in utilizing bainitic microstructures in structural applications at a wide variety of strength levels. By varying the carbon content, alloying additions, and temperature of transformation, the strength of bainite can be varied from that of ferrite-pearlite aggregates to nearly that of martensite. The variation in strength reflects the variation in grain size and carbide size and distribution.

The strength of lower bainite is dependent upon the carbon content in much the same manner as the strength of martensite. However, bainite of a given carbon content has lower strength than martensite of the same carbon level (1). The final strength of lower bainite is very sensitive to the transformation temperature. This probably accounts for the wide variety of properties reported for this microstructure.

Not all steels develop lower bainitic microstructures. Recent research by White and Owen (2) showed that lower bainite forms only below 660°F for both a eutectoid plain carbon steel and a 0.33% carbon Ni-Cr steel. They also confirmed the data of Radcliffe and Rollason (3) that the activation energies are different for upper and lower bainite. Thus, steels with M_s temperatures near or above 660°F cannot be transformed to lower bainite.

Considerable controversy exists over the properties and practical value of bainitic microstructures. Advantages are believed to include less residual stress and distortion, better ductility, and fewer internal microcracks which accompany the formation of martensite. Disadvantages seem to be the lower strength for a given carbon content and perhaps the much closer control of chemistry and heat treating variables necessary to obtain reproducible properties.

The subject was reviewed several years ago by Hehemann et al. (4). Nothing has been reported recently, since the advent of the Irwin-Griffith techniques for measuring fracture toughness of sheet material. The present program was undertaken to obtain evidence on the fracture toughness of ultra-high strength steel in both bainitic and tempered martensitic microstructures for several different steel compositions.

II. EXPERIMENTAL WORK

All the experimental steels in this program were induction-melted in a basic-lined crucible. The SAE 4350, 4360, and 4370 steels were 100 lb heats; the remainder were 500 lb heats. The charge was composed of Armco

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ingot iron and ferroalloys. Final deoxidation was accomplished by the addition of 2 lb/ton of Al. After stripping the ingots from the 9 in.^{2} mold, they were slowly cooled in sand. The ingots were hot forged to 1 in. slab and hot rolled to 1/2 in. plate. The scale and decarburized layers were completely removed, and the plate was reduced to 0.080 in. sheet by warm rolling at 1000-1200°F. Sheet tensile and sheet center-notched specimens were machined, and all final austenitizing was performed in an argon atmosphere. Metallographic examination and hardness tests showed no evidence of decarburization. The compositions of these experimental steels are shown in Table 1.

Initial work was conducted on all the experimental steel to determine the M_s temperatures and the isothermal reaction starting and ending times. The M_s temperatures were determined by the Greninger-Troiano technique. The isothermal reaction times were determined by optical microscopy and hardness changes. These data for the SAE 4360, 1Cr-1Mo, 3.5Ni, and 9Ni-4Co steels are tabulated in Table 2.

After austenitizing, the smooth and the center-notched tensile specimens were either oil-quenched or isothermally transformed in molten salt. The specimens were cooled in liquid nitrogen immediately after heat treatment and tempered for one hour at a preselected temperature. This deep-freeze and tempering operation was repeated as an added precaution in eliminating retained austenite.

All tensile specimens were tested at room temperature. The center-notched specimens were filed to a notch radius of 0.001 in. or less before testing. These notch radii were checked at high magnification for accuracy and uniformity.

The center-notched test specimen data were evaluated by calculating K_c and G_c values according to the methods recommended by ASTM (5). The values of K_c were obtained from the relationship:

$$K_c = \sigma \sqrt{qw}$$

where σ (ksi) is the gross section stress, w is the test specimen width, and q is obtained from the relationship:

$$\frac{\pi a}{w} \text{ vs. } \left[\frac{\sigma}{\sigma_y}\right]^2$$

where a is one half the total crack length at onset of fast crack growth and σ_y is the yield strength. The crack length was determined by the ink-stain technique. G_c values were calculated from the relationship:

$$G_c = \frac{K_c^{\,2}}{E}$$

where E is Young's modulus.

A. SAE 43XX Steels

The SAE 43XX steels were studied primarily to determine the carbon content required to obtain ultra-high strength bainitic microstructures. It appeared from the literature that more than 0.40% C would be required to develop yield strengths above 200,000 psi. Three steels with 0.50, 0.60, and 0.70% C were made for this purpose.

The SAE 43XX steels were isothermally transformed above and below the M_s temperatures of each steel. The resulting yield strengths and K_c and G_c values are listed as a function of transformation temperature in Table 3. The SAE 4350 steel had a reasonably good combination of strength and toughness, although not superior to quenched and tempered steels. The SAE 4360 and 4370 steels developed high yield strengths, but their toughness was poor.

From these data on SAE 43XX steels it appears that a carbon content of about 0.60% would be required to obtain yield strengths up to 240,000 psi by isothermal transformation to lower bainite. Further work was not performed with these steels because of banding problems as a result of the small amount of hot work on these 100 lb ingots.

Three additional alloy steels with approximately 0.60% C were made to study the effect of various alloying elements on the yield strengths and fracture toughness of isothermally transformed bainitic microstructures. These steels were made in 500 lb heats, forged and hot rolled to 1/2 in. plate and warm rolled to 0.080 in. sheet. The tensile properties and fracture toughness data are discussed separately for each steel.

B. 1Cr-1Mo (D6 Type) Steel

D6 is a relatively new grade of steel with sufficient hardenability to develop a satisfactory microstructure in thin section sizes with a mild quench and has been used successfully as a ballistic missile steel. Because of its alloy content it can be tempered at high temperatures to eliminate or minimize residual quenching stresses and yet maintain a high level of strength and toughness. The carbon content of the steel investigated in this program was increased to permit the development of ultra-high strengths in the bainitic condition.

Both smooth sheet tensile and center-notched sheet tensile specimens were heat treated by isothermal transformation to lower bainite and by oil quenching to martensite. The isothermal treatments were performed at various temperatures from 500 to 650°F. These specimens were given a double refrigeration and tempering treatment. The oil-quenched specimens were tempered at 400 to 950°F to cover a range of yield strengths comparable to those obtained by isothermal transformation. The resulting tensile properties are listed in Table 4 and plotted as a function of the transformation or the tempering temperature in Figure 1.

The strength properties of the isothermally transformed specimens decreased linearly and very rapidly with increasing transformation temperature. The 0.2% yield strength decreased from about 250,000 psi for the 500°F

treatment to 186,500 psi for the 650°F treatment. The oil-quenched specimens showed an initial rapid decrease in strength with increasing temperature up to 650°F. Above this temperature the tempering rate slowed considerably.

The fracture toughness data for both the isothermally transformed and the quenched and tempered specimens are shown in Table 5, and are plotted as a function of the transformation or the tempering temperature in Figure 2. The G_c values were fairly low for specimens transformed below 600°F. At 600°F, however, there was a rapid increase in G_c to values as high as 3000 in.-lb/in.^{2} This rapid change in G_c was accompanied by considerable scatter in the data. Since the M_s temperature of this steel is 575°F, the low values of G_c at temperatures below 600°F may be caused by the presence of martensite. Above 600°F no martensite forms and the yield strength values are at or below 200,000 psi. The accompanying G_c values are above 3500 in.-lb/in.^{2} The scatter at 600°F may reflect the formation of stress-induced martensite in some instances (6).

The quenched and tempered specimens exhibit an exponential increase in G_c with increasing tempering temperature. The G_c values were less than 600 in.-lb/in.^{2} for tempering temperatures below 650°F. The values increased very rapidly with increasing tempering temperatures above 800°F.

Comparison of the bainitic and tempered martensitic structures in this steel at constant yield strength levels shows that bainite is always inferior to the martensite. For example, at 220,000 psi yield strength the G_c value is approximately 500 to 600 in.-lb/in.^{2} for bainite and over 2000 in.-lb/in.^{2} for martensite. At slightly lower yield strength levels (212,000 psi) where 100% bainite formed above the M_s, the bainite had G_c values of approximately 1600 in.-lb/in.^{2} and the martensite was over 2500 in.-lb/in.^{2}

The microstructures of lower bainite and martensite at approximately equal yield strength levels (210,000 psi) are shown in Figure 3. Both microstructures had good fracture toughness although the martensite is superior. The major difference in structure is the coarser particle size of the bainite.

C. 3.5Ni Steel

A 3.5Ni-0.58C steel was made to determine the strength and toughness behavior in a straight nickel composition and to obtain a steel with a lower M_s temperature (500°F) than the 1Cr-1Mo alloy. Smooth sheet tensile and center-notched tensile specimens were isothermally transformed in the temperature range 500 to 600°F. Oil-quenched specimens were tempered at various temperatures from 550 to 750°F. The tensile properties after these various heat treatments are shown in Table 6, and the 0.2% yield strengths are plotted in Figure 4.

The yield strengths of the lower bainite varied from 232,900 to 184,400 psi when the isothermal transformation temperature was increased from 500 to 600°F. This rate of change of strength with temperature is

approximately the same as that for the 1Cr-1Mo steel although the absolute strength values are lower for the 3.5Ni steel. For example, after transforming at 600°F, the nickel steel had a yield strength of 184,400 psi compared with about 210,000 psi for the 1Cr-1Mo steel. The oil-quenched specimens show a rapid decrease in strength with increasing tempering temperature which is expected in the absence of temper-retarding alloying elements.

The fracture toughness data for the 3.5Ni steel are listed in Table 7 and plotted in Figure 5. Bainite formed at 500°F had fairly low toughness (G_c = 427 in.-lb/in.^{2}), whereas bainite formed at 525 to 600°F had about equal G_c values in the region of 1650 in.-lb/in.^{2} The toughness for the structure formed at 500°F follows the same trend noted in the 1Cr-1Mo steel: bainite formed near or below the M_s has low values of fracture toughness. Bainite formed in the 3.5Ni steel at 525 to 600°F has adequate toughness at yield strengths as high as 219,900 psi. The principal factor in developing this good combination of properties in lower bainite is believed to be the low temperature (525°F) at which completely bainitic structures can be formed in the 3.5Ni steel.

It is interesting to observe the fracture toughness behavior of the 3.5Ni steel in the tempered martensitic condition. The G_c values were very low, varying from 97 to 291 in.-lb/in.^{2} as the tempering temperature was increased from 550 to 650°F. At tempering temperatures of 700 and 725°F the G_c values increased to about 1450 in.-lb/in.^{2} It appears that some microstructural change has occurred at these higher tempering temperatures which significantly affects the fracture toughness with only a slight change in yield strength.

D. 9Ni-4Co Steel

There has been interest recently in a high-nickel, cobalt steel at intermediate carbon contents (7). A higher carbon version of this steel was made to study the strength and fracture toughness behavior in isothermally transformed and quenched and tempered specimens.

Specimens were isothermally transformed at temperatures between 500 and 600°F. Oil-quenched specimens were tempered at 550 to 750°F. The tensile properties are shown in Table 8 and Figure 6. The isothermally transformed specimens exhibit very low tensile strengths compared with other high-carbon alloy steels. A major microstructural difference between the 9Ni-4Co steel and other alloy steels is shown in Figure 8 where a comparison is made with the 3.5Ni steel in the partially reacted condition and in Figure 9 for fully reacted material. The bainite formed at 500 to 600°F in the 9Ni-4Co steel is atypical for low alloy steels and appears to resemble a higher temperature type of bainite. Cobalt, which is known to accelerate the pearlite reaction, appears to lower the temperature range of intermediate bainite formation. Recent work by Chandhok et al. (8) has shown that cobalt increases the activity of carbon in both austenite and ferrite. This increased activity coefficient may account for the faster growth rate in pearlite and perhaps the observed change in the bainite reaction, also.

The quenched and tempered specimens had typical mechanical properties as a function of tempering temperature. They show the usual rapid decrease with increasing tempering temperature from nearly 240,000 psi at 550°F to 200,000 at 750°F.

The fracture toughness data for the 9Ni-4Co steel are shown in Table 9 and Figure 7. The G_c values for the isothermally transformed specimens were very low and practically constant at 275 in.-lb/in.^{2} for transformation temperatures from 500 to 600°F. Undoubtedly, this low fracture toughness is associated with the atypical bainite in this steel. The tempered martensite also had low fracture toughness at tempering temperatures up to 750°F. The increase in G_c which usually occurs with increasing tempering temperature is apparently delayed to temperatures above 750°F for this steel.

E. Yield Strength to Ultimate Strength Ratio

The yield strength to ultimate strength ratio has been plotted in Figure 10 for both the bainitic and tempered martensitic structures of the 1Cr-1Mo, 3.5Ni, and 9Ni-4Co steels. The ratios for the bainitic structures decreased with increasing transformation temperature and were in the range 0.85 to 0.90 for the 1Cr-1Mo and 3.5Ni steels. The 9Ni-4Co steel had lower ratios, which is consistent with the microstructure of this steel.

The ratios for the tempered martensitic structures increased with tempering temperature to a maximum which was about 850 and 700°F for the 1Cr-1Mo and 3.5Ni steels, respectively. The 9Ni-4Co steel had not reached the maximum at 750°F, the highest tempering temperature studied. It is interesting to note that G_c values of approximately 1500 in.-lb/in.^{2} were obtained in both the 1Cr-1Mo and the 3.5Ni steels at the tempering temperatures which produced the maximum in the yield strength to ultimate strength ratios.

F. Discussion

The data presented on bainitic microstructures has shown that carbon contents of 0.55 to 0.60% or higher are required to produce ultrahigh strength levels. The yield strengths vary as a function of the isothermal transformation temperature and the chemistry of the steel. The strengths decreased about 10,000 psi for each 25°F increase in transformation temperature. The presence of strong carbide formers produces a higher strength bainite for a given transformation temperature.

The fracture toughness behavior of bainite depended upon the transformation temperature and strength level. For transformation temperatures at least 25°F above the M_s temperature, bainitic structures had good toughness with G_c values of 1500 in.-lb/in.^{2} or higher. For the 1Cr-1Mo steel with an M_s temperature of 575°F, this required transformation at 600°F or higher. At these high transformation temperatures the yield strength was 210,000 psi or less. The 3.5Ni steel, which had a lower M_s temperature (500°F), had good fracture toughness in bainite formed as low as 525°F, where the yield strength was about 220,000 psi. Unfortunately, the 9Ni-4Co steel did not transform to a typical lower bainite at temperatures just above the M_s.

A comparison of the strength-fracture toughness relationship for both bainite and tempered martensite is shown in Figure 11. The curve is for data from the literature (9, 10) on tempered martensite for several typical alloy steels. The SAE 43XX steels all show somewhat lower fracture toughness for bainitic structures when compared with tempered martensite at the same strength level. Similar results were reported recently by Banerjee and Hauser (11) for SAE 4340. In their study bainite formed at 600°F was compared with martensite tempered at 850°F. Both structures had 0.2% yield strengths of 190,000 psi.

The lower bainite in the 1Cr-1Mo steel has slightly lower fracture toughness than martensite of the same strength level for yield strengths above 220,000 psi. Below 220,000 psi the bainite has somewhat better toughness than the typical alloy martensite but less than martensite in the same 1Cr-1Mo steel.

The best combination of strength-fracture toughness in the 3.5Ni steel occurred in a bainitic microstructure at 220,000 psi yield strength (formed at 525°F). The fracture toughness was significantly higher than that for a typical martensite at this strength level, although it is still below the toughness obtained for the 1Cr-1Mo martensite. At lower yield strengths the fracture toughness of lower bainite in the 3.5Ni steel is comparable with tempered martensite.

The 9Ni-4Co steel had low fracture toughness for every heat treatment studied. The low strengths and low fracture toughness values of the isothermally transformed specimens were apparently caused by the displacement of the bainitic reaction. The tempered martensite had unusually low fracture toughness even after tempering as high as 750°F, which produces a yield strength of about 200,000 psi.

III. SUMMARY

The tensile properties and fracture toughness have been measured for isothermally transformed bainite in a series of alloy steels. Bainite was formed both above and below the M_s temperatures in SAE 4350, 4360, and 4370 steels to determine the carbon content required to produce ultra-high strength levels. Carbon contents from 0.55 to 0.60% were selected for producing the desired yield strengths.

Three additional alloy steels were made to study the effect of chemistry on the properties of bainite. These compositions were 1Cr-1Mo, 3.5Ni, and 9Ni-4Co. Tensile and fracture toughness properties were measured in these sheet steels as a function of isothermal transformation temperature for bainite and tempering temperature for martensite. The yield strengths of the isothermally treated samples were a linear function of the transformation temperature with a rate of approximately 10,000 psi

per 25°F. The martensitic structures were tempered over a temperature range to produce yield strengths comparable to those obtained in the bainitic structures.

Several trends in the fracture toughness results were noted:

1. Bainite formed just above or below the M_s temperature had low fracture toughness.

2. Bainite formed more than 25°F above the M_s exhibited good toughness.

3. The fracture toughness-yield strength combination for bainite formed above the M_s temperature was generally comparable to or somewhat better than the published data on a variety of martensitic steels, although not as good as the martensite of the 1Cr-1Mo steel in this investigation.

4. Tempered martensite in the 1Cr-1Mo steel was superior in fracture toughness to other low alloy steels at yield strengths below 240,000 psi.

5. The high-carbon martensitic steels, containing no carbide formers, had low fracture toughness at strength levels above 210,000 or 220,000 psi.

The 9Ni-4Co steel developed an intermediate type of bainite when transformed at temperatures near the M_s temperature. The fracture toughness of this microstructure was very low for all transformation temperatures studied. This alloy steel had low fracture toughness for martensitic structures tempered at temperatures as high as 750°F.

IV. CONCLUSIONS

Carbon contents of 0.55 to 0.60% or higher are required to produce lower bainite with ultra-high strengths in low alloy steels. Bainite formed below or just above the M_s temperature has slightly lower fracture toughness than tempered martensite at equal strength levels. Bainite formed more than 25°F above the M_s temperature has fracture toughness equal to or slightly better than tempered martensite.

It is concluded that lower bainite cannot provide significant improvement in fracture toughness in low alloy steels. Although some steels (3.5Ni) can develop the best combination of strength-toughness in a bainitic microstructure, this combination is not superior to tempered martensite in other steels (1Cr-1Mo).

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TABLE 1

COMPOSITIONS OF EXPERIMENTAL STEELS

Steel	Composition, w/o				
	C	Ni	Cr	Mo	Co
SAE 4350	0.48	1.8	0.75	0.25	----
SAE 4360	0.60	1.75	0.8	0.20	----
SAE 4370	0.72	1.79	0.8	0.25	----
1Cr-1Mo	0.54	0.2	0.9	1.0	----
3.5Ni	0.58	3.54	0.25	0.25	----
9Ni-4Co	0.59	8.9	----	----	3.6

TABLE 2

M_s TEMPERATURE DETERMINATIONS
AND ISOTHERMAL TRANSFORMATION DATA

Alloy Steel	M_s Temp., °F		Isothermal Transformation Times at Indicated Temperatures (°F), min				
			600	550	500	450	400
SAE 4360	470	Start	1.5	3	8	25	60
		Finish	1500	700	700	1500	3000
1Cr-1Mo	575	Start	1	1	1	2	5
		Finish	20	30	60	120	250
3.5Ni	500	Start	3	15	30	240	---
		Finish	60	--	240	1000	---
9Ni-4Co	525	Start	60	60	90	150	---
		Finish	600	600	300	---	---

TABLE 3

THE FRACTURE TOUGHNESS OF CENTER-NOTCHED SPECIMENS OF ISOTHERMALLY TRANSFORMED SAE 43XX STEELS*

Steel	Transformation Temperature, °F	0.2% Yield Strength, psi	K_c, ksi $\sqrt{in.}$	G_c, in.-lb/in.^{2}
4350	550	220,000	169	957
	550	220,000	160	855
4350	500	228,000	147	715
	500	228,000	157	822
4360	500	242,000	83	229
	500	242,000	78	202
4360	450	257,000	77	199
	450	257,000	62	127
4370	500	250,000	68	156
	500	250,000	88	258
4370	450	272,000	59	115
	450	272,000	61	126

* All specimens transformed for 24 hours and double tempered at 550°F one hour with -320°F treatment before each tempering operation.

TABLE 4

THE TENSILE PROPERTIES OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 1Cr-1Mo STEEL

Spec. No.	Heat Treatment*	Ultimate Tensile Strength, psi	0.2% Offset Yield Strength, psi	Elongation in 2 in., %
2-6	IT-500°F, 24 hr	295,830	252,100	4
2-2	IT-550°F, 24 hr	263,750	228,330	6
2-11	IT-550°F, 24 hr	270,500	227,800	5
2-17	IT-575°F, 24 hr	257,400	219,800	4
2-4	IT-600°F, 24 hr	236,660	200,000	6
2-13	IT-600°F, 24 hr	248,100	212,700	7
2-21	IT-625°F, 20 hr	232,900	196,300	5
2-18	IT-650°F, 7 hr	220,800	186,500	4
2-8	Q and T-400°F	330,100	275,500	4
2-1	Q and T-550°F	292,900	260,400	5
2-14	Q and T-650°F	272,200	240,500	6
2-15	Q and T-750°F	258,800	236,500	3
2-22	Q and T-850°F	244,100	223,100	3
2-9	Q and T-900°F	240,800	219,400	4
2-16	Q and T-900°F	235,350	219,800	3
2-19	Q and T-950°F	230,600	212,900	5

* All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

TABLE 5

THE FRACTURE TOUGHNESS OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 1Cr-1Mo STEEL

Spec. No.	Heat Treatment*	0.2% Offset Tensile Yield Strength, psi	K_c, ksi $\sqrt{in.}$	Gc, in.-lb/in.^{2}	Shear, %
2-6	IT-500°F, 24 hr	252,100	98	317	30
2-7	IT-500°F, 24 hr	252,100	97	313	30
2-2	IT-550°F, 24 hr	228,330	138	631	50
2-3	IT-550°F, 24 hr	228,300	134	596	50
2-11	IT-550°F, 2 hr	227,800	115	444	75
2-17	IT-575°F, 24 hr	219,900	109	394	75
2-4	IT-600°F, 24 hr	200,000	304	3076	80
2-5	IT-600°F, 24 hr	200,000	145	954	80
2-13	IT-600°F, 24 hr	212,700	225	1683	100
2-12	IT-600°F, 2 hr	213,600	216	1553	100
2-21	IT-625°F, 20 hr	196,300	131	571	50
2-20	IT-625°F, 20 hr	196,300	---	---	100
2-18	IT-650°F, 7 hr	186,500	---	---	100
2-8	Q and T-400°F	275,500	60	118	20
2-1	Q and T-550°F	260,400	104	363	50
2-14	Q and T-650°F	240,500	131	574	80
2-15	Q and T-750°F	236,500	160	849	80
2-22	Q and T-850°F	228,100	214	1526	70
2-9	Q and T-900°F	219,400	210	1470	100
2-16	Q and T-900°F	219,800	256	2177	100
2-19	Q and T-950°F	212,900	284	2693	100

*All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

TABLE 6

THE TENSILE PROPERTIES OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 3.5Ni STEEL

Spec. No.	Heat Treatment*	Ultimate Tensile Strength, psi	0.2% Offset Yield Strength, psi	Elongation in 2 in., %
1X-14	IT-500°F, 24 hr	258,500	232,900	5
1X-11	IT-525°F, 24 hr	247,000	219,900	4
1X-2	IT-550°F, 24 hr	231,700	20[illegible],800	7
1X-3	IT-550°F, 3 hr	241,600	211,200	7
1X-8	IT-575°F, 24 hr	213,300	189,800	4
1X-4	IT-600°F, 1 hr	211,800	184,400	6
1X-1	Q and T-550°F	280,700	253,500	4
1X-9	Q and T-600°F	264,000	241,900	3
1X-5	Q and T-650°F	228,600	212,600	5
1X-12	Q and T-700°F	216,700	203,000	4
1X-10	Q and T-700°F	221,400	207,400	4
1X-13	Q and T-725°F	215,100	200,000	6
1X-6	Q and T-750°F	203,400	182,600	6

*All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

TABLE 7

THE FRACTURE TOUGHNESS OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 3.5Ni STEEL

Spec. No.	Heat Treatment*	0.2% Offset Tensile Yield Strength, psi	K_c, ksi $\sqrt{in.}$	G_c, in.-lb/in.^{2}	Shear, %
1X-14	IT-500°F, 24 hr	232,900	113	427	70
1X-11	IT-525°F, 24 hr	219,900	223	1655	90
1X-2	IT-550°F, 24 hr	207,800	221	1624	100
1X-3	IT-550°F, 3 hr	211,200	151	757	70
1X-8	IT-575°F, 24 hr	189,800	227	1716	100
1X-4	IT-600°F, 1 hr	184,350	**	**	**
1X-1	Q and T-550°F	253,500	54	97	20
1X-9	Q and T-600°F	241,900	76	194	20
1X-5	Q and T-650°F	212,600	93	291	80
1X-12	Q and T-700°F	203,000	208	1443	100
1X-10	Q and T-700°F	207,400	202	1354	100
1X-13	Q and T-725°F	200,000	213	1516	100
1X-6	Q and T-750°F	182,600	**	**	**

* All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

** Specimen broke in grips.

TABLE 8

THE TENSILE PROPERTIES OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 9Ni-4Co STEEL

Spec. No.	Heat Treatment*	Ultimate Tensile Strength, psi	0.2% Offset Yield Strength, psi	Elongation in 2 in., %
3X-6	IT-500°F, 48 hr	231,800	192,900	6
3X-9	IT-525°F, 24 hr	222,400	183,400	8
3X-2	IT-550°F, 24 hr	207,100	170,100	8
3X-3	IT-600°F, 24 hr	190,700	155,000	9
3X-1	Q and T-550°F	276,000	237,500	6
3X-7	Q and T-600°F	266,400	237,000	5
3X-4	Q and T-650°F	244,100	218,700	5
3X-8	Q and T-700°F	225,800	205,900	5
3X-5	Q and T-750°F	215,500	199,500	6

*All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

TABLE 9

THE FRACTURE TOUGHNESS OF ISOTHERMALLY TRANSFORMED AND QUENCHED AND TEMPERED 9Ni-4Co STEEL

Spec. No.	Heat Treatment*	0.2% Offset Tensile Yield Strength, psi	K_c, ksi $\sqrt{in.}$	G_c, in.-lb/in.^{2}	Shear, %
3X-6	IT-500°F, 48 hr	192,900	91	274	20
3X-10	IT-500°F, 48 hr	192,900	92	285	20
3X-9	IT-525°F, 24 hr	183,400	90	271	25
3X-2	IT-550°F, 24 hr	170,100	90	272	20
3X-3	IT-600°F, 24 hr	155,000	75	187	0
3X-1	Q and T-550°F	237,500	59	114	20
3X-7	Q and T-600°F	237,000	72	175	20
3X-4	Q and T-650°F	218,700	64	137	20
3X-8	Q and T-700°F	205,900	80	214	20
3X-5	Q and T-750°F	199,500	89	264	25

*All specimens double tempered for one hour at indicated temperature with -320°F treatment before each tempering operation. The IT (isothermally transformed) specimens were tempered at 550°F or at the transformation temperature if above 550°F.

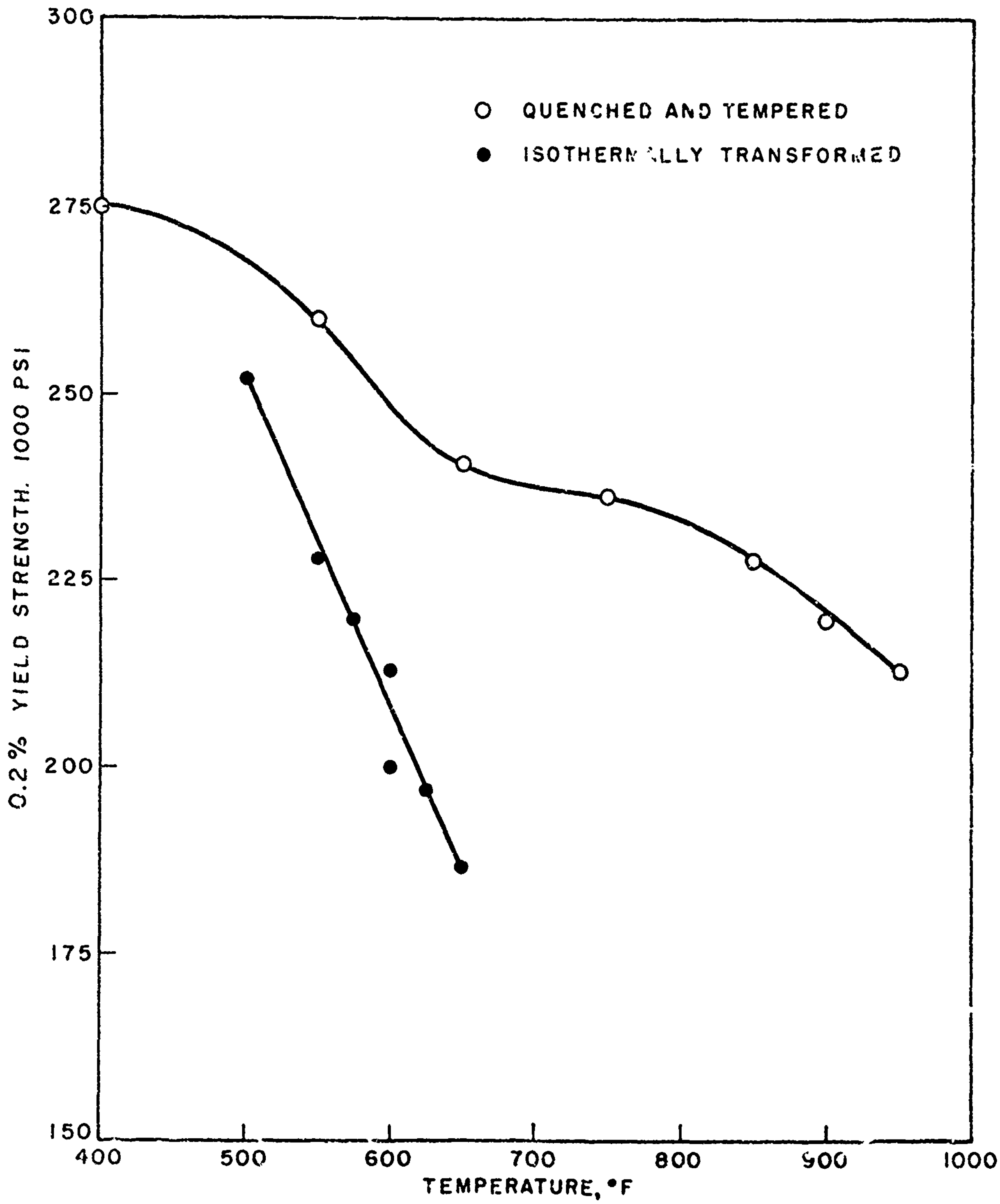


FIG. 1 - THE 0.2% YIELD STRENGTH AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 1Cr-1Mo STEEL.

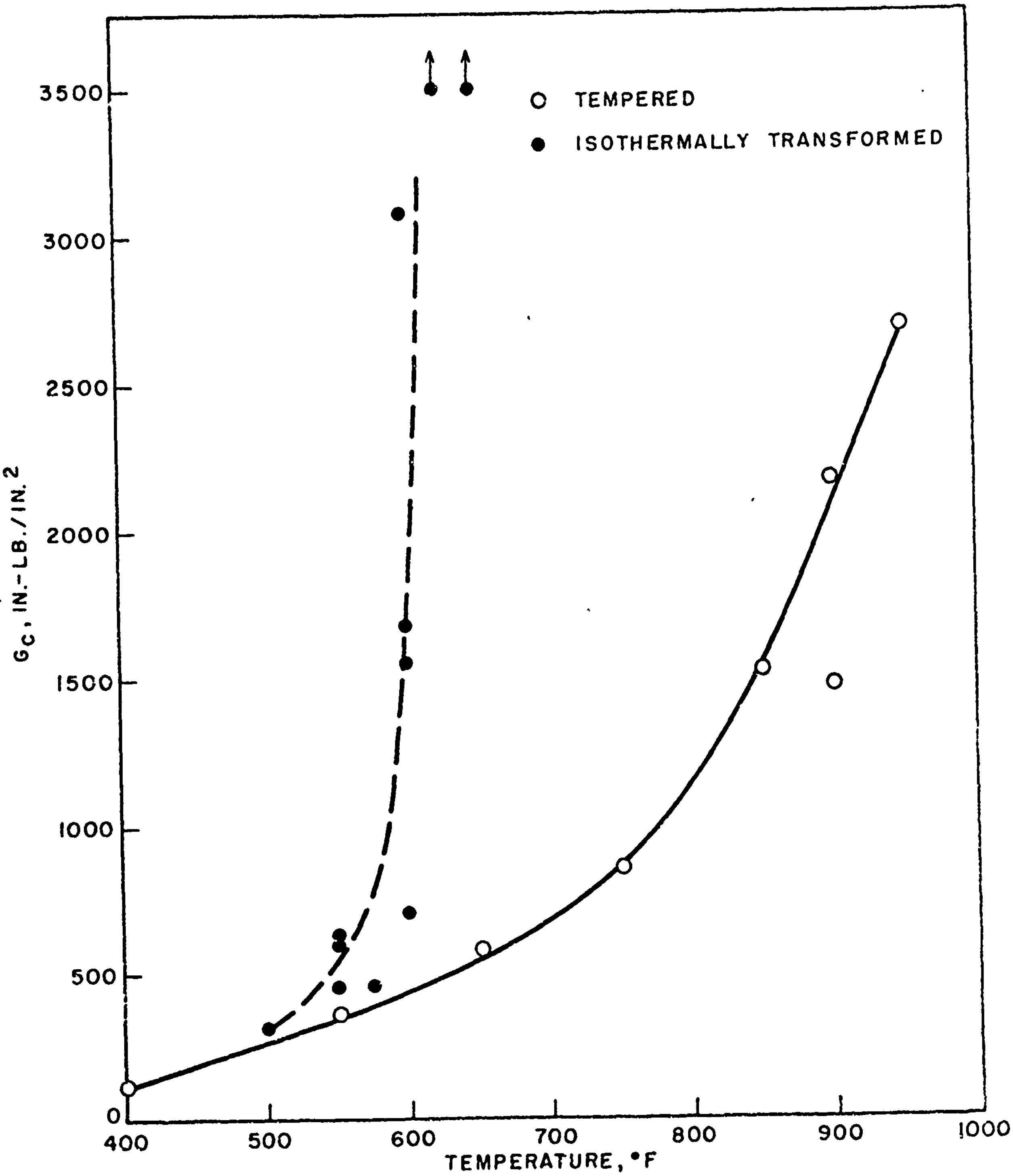
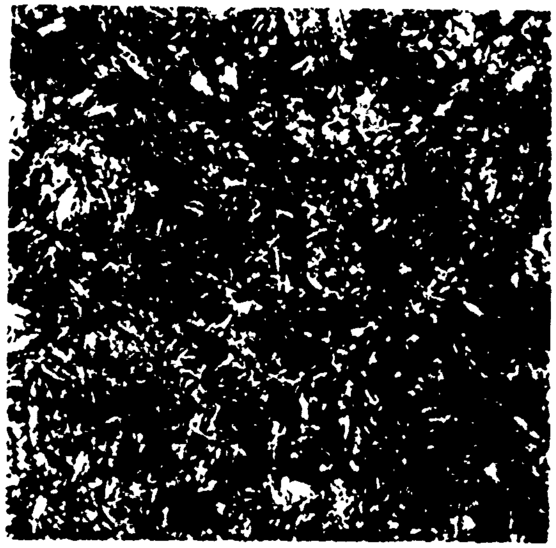


FIG. 2 - G_c AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 1Cr-1Mo STEEL.



Neg. No. 24793 Mag. 1000X

(a) Martensite Tempered at 950°F.

Neg. No. 24794 Mag. 1000X

(b) Bainite Formed at 600°F.

FIG. 3

TYPICAL MICROSTRUCTURES OF 1Cr-1Mo STEEL AT APPROXIMATELY EQUAL STRENGTH VALUES.

Etchant: Nital

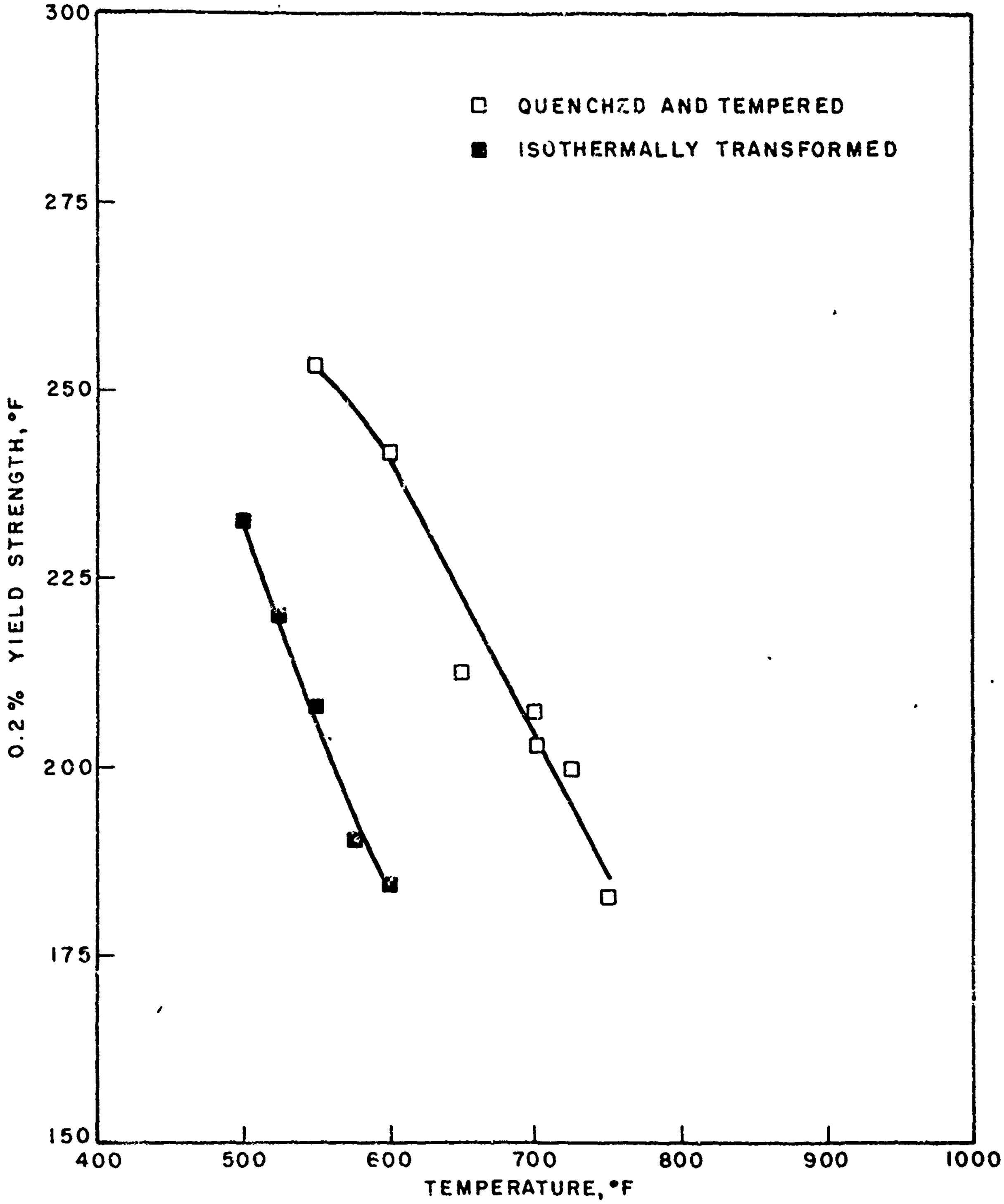


FIG. 4 - THE 0.2% YIELD STRENGTH AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 3.5Ni STEEL

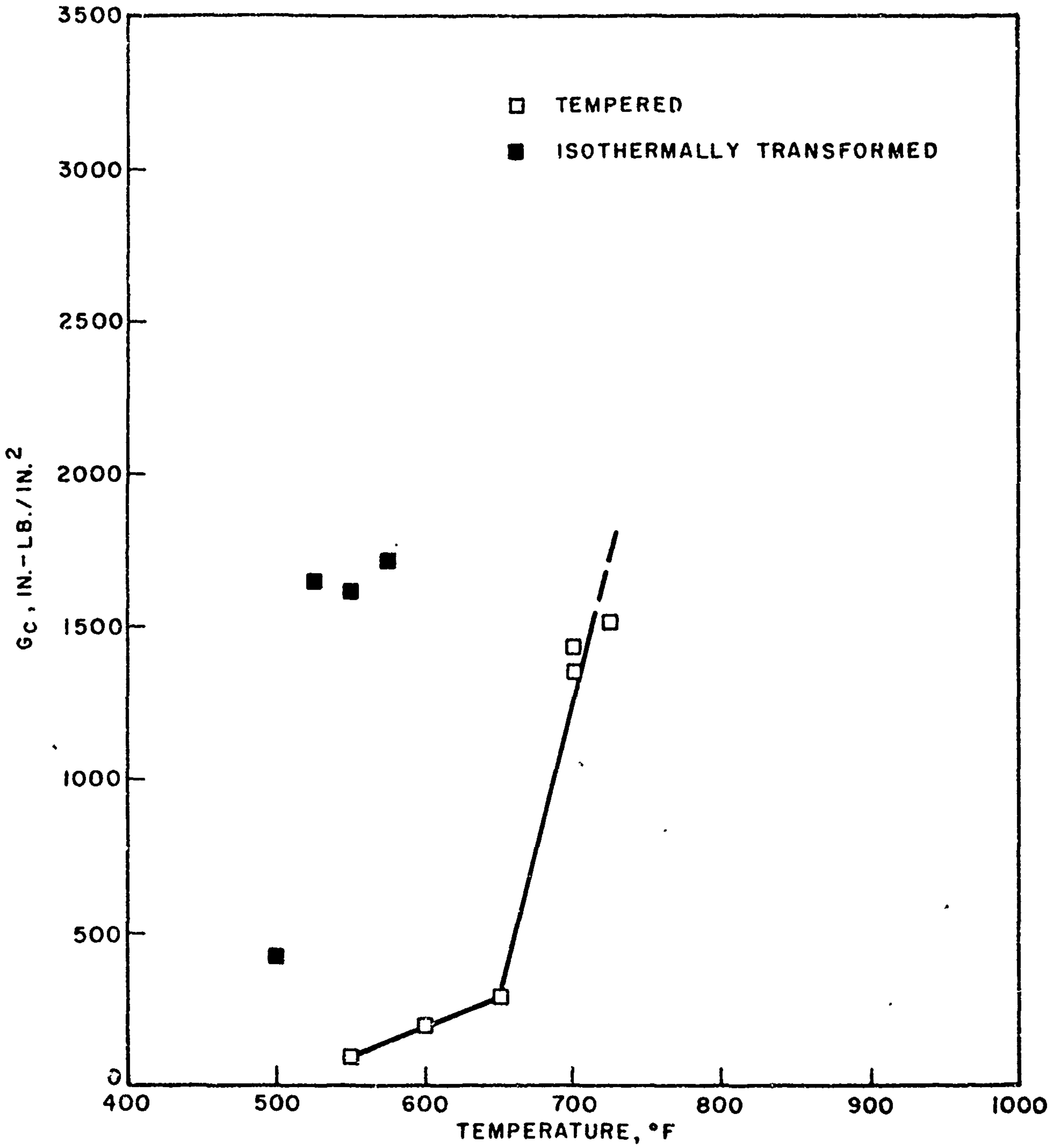


FIG. 5- G_c AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 3.5Ni STEEL.

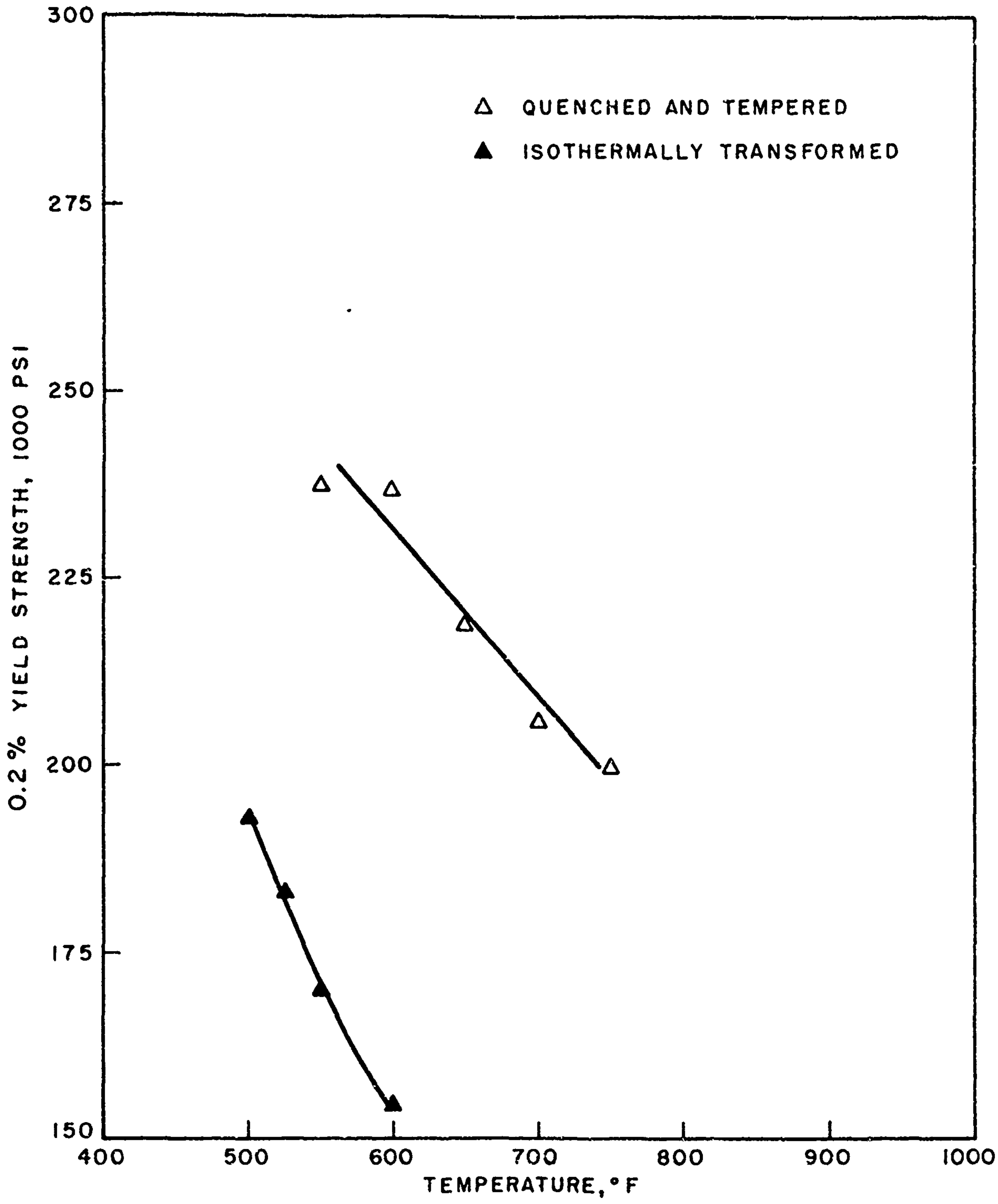


FIG. 6 - THE 0.2% YIELD STRENGTH AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 9Ni-4Co STEEL.

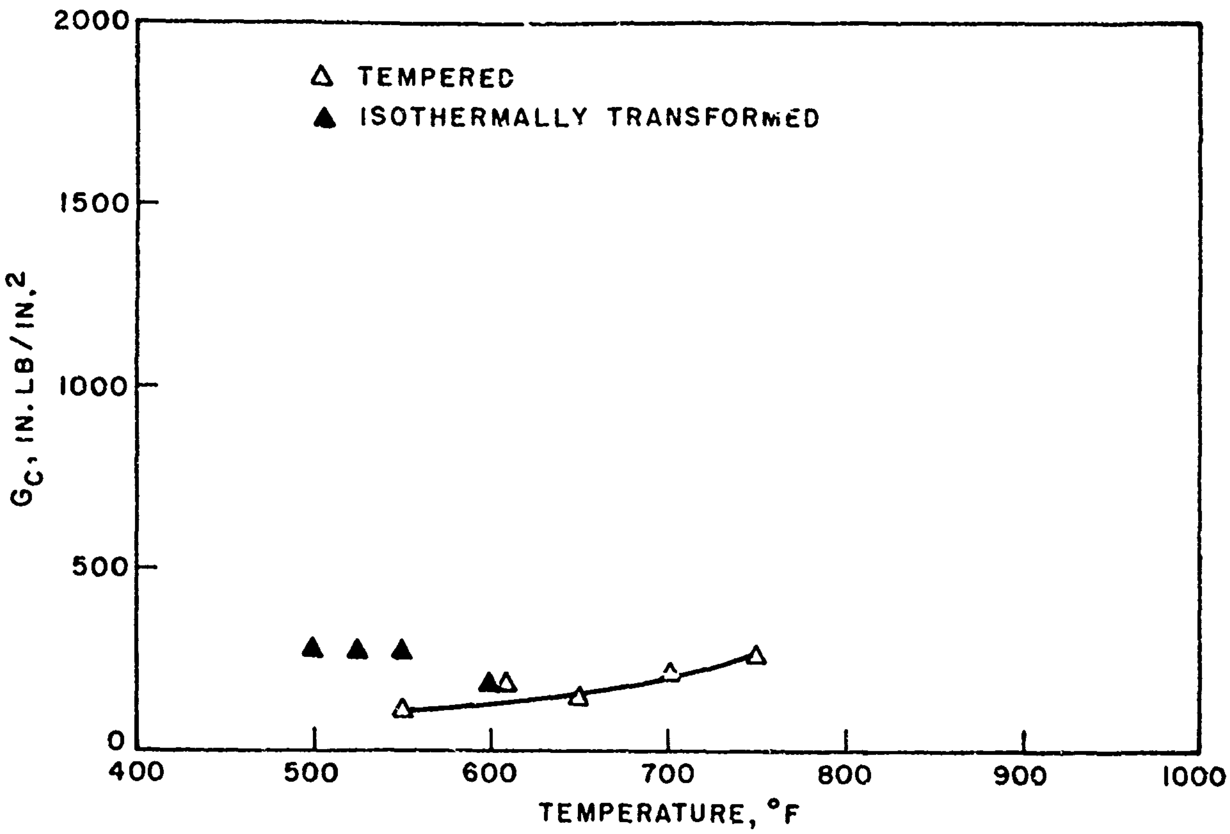


FIG. 7 - G_c AS A FUNCTION OF TEMPERING OR ISOTHERMAL TRANSFORMATION TEMPERATURE FOR THE 9Ni-4Co STEEL.

Neg. No. 24790 Mag. 1000X

(a) Bainite Formed at 550°F in the 3.5Ni Steel.

Neg. No. 24866 Mag. 1600X

(b) Bainite Formed at 550°F in the 9Ni-4Co Steel.

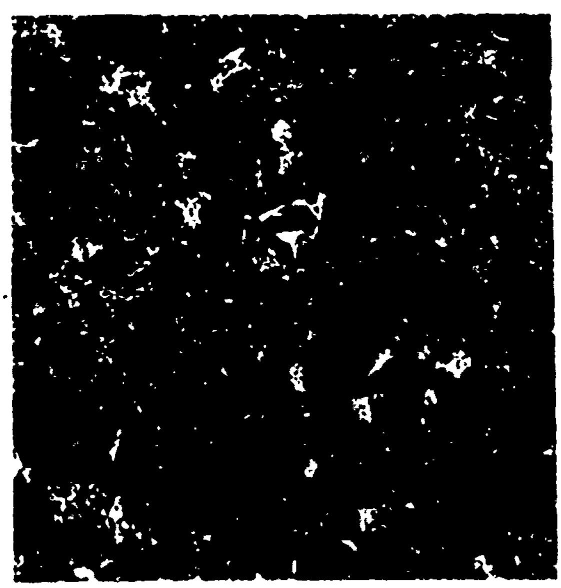
FIG. 8

PARTIALLY REACTED BAINITE IN 3.5Ni AND 9Ni-4Co STEELS AT 550°F.

Etchant: Nital

Neg. No. 24789 Mag. 1000X

(a) Bainite Formed at 550°F in the 3.5Ni Steel.



Neg. No. 24786 Mag. 1000X

(b) Bainite Formed at 550°F in the 9Ni-4Co Steel.

FIG. 9

FULLY REACTED BAINITE IN THE 3.5Ni AND 9Ni-4Co STEELS AT 550°F.

Etchant: Nital

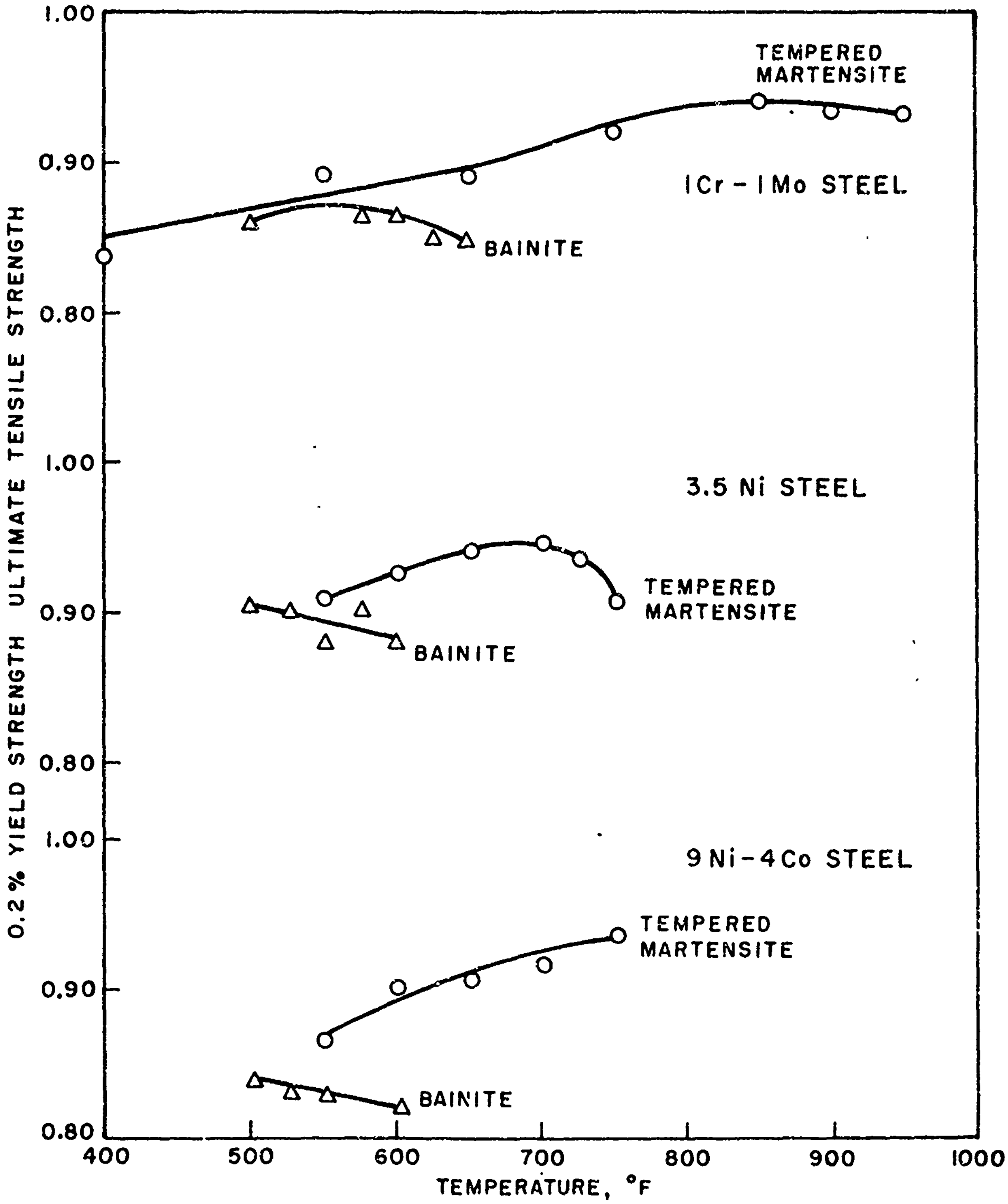


FIG. 10 - THE YIELD STRENGTH/ULTIMATE STRENGTH RATIO FOR VARIOUS STEELS AND HEAT TREATMENTS.

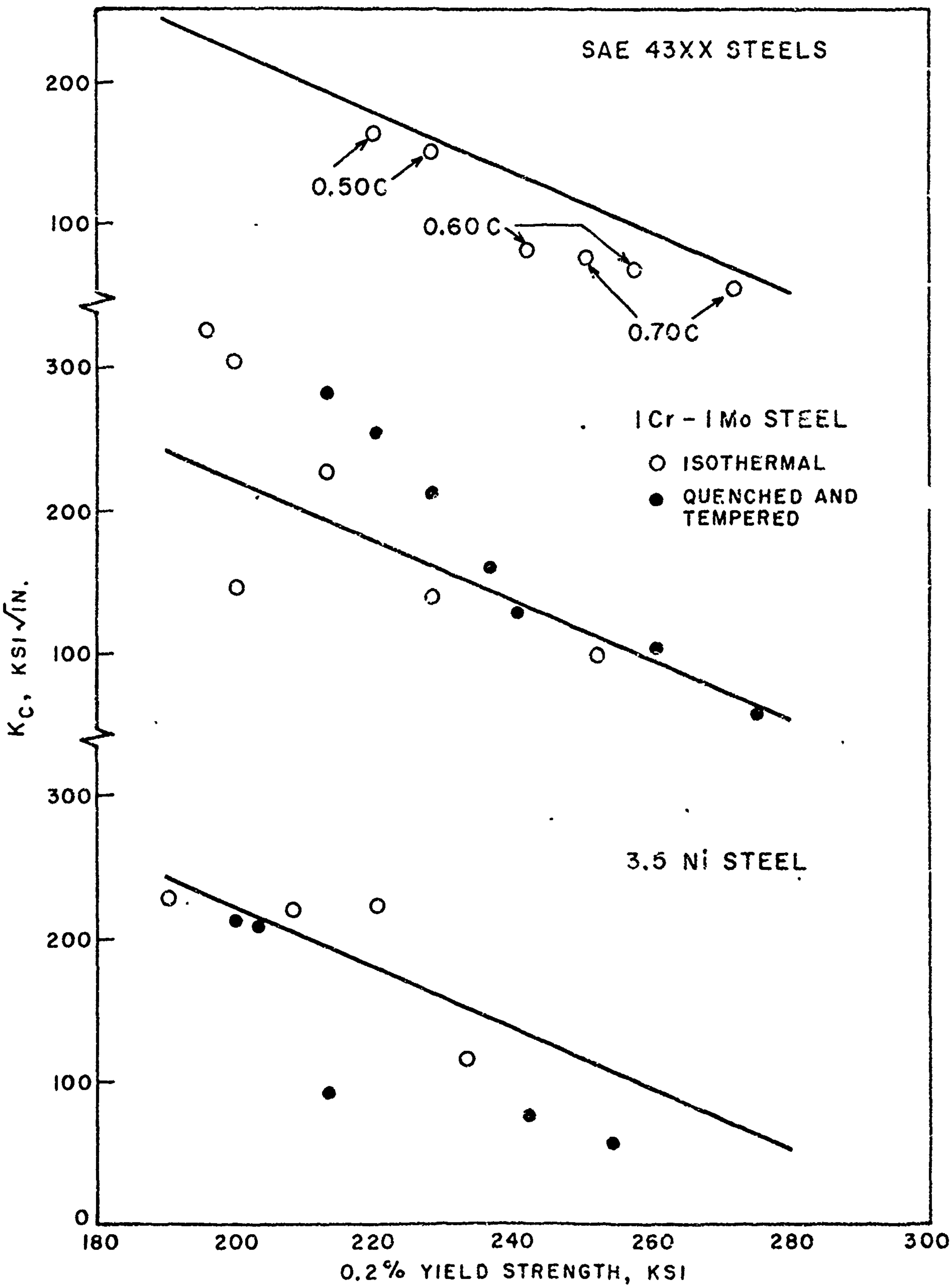


FIG. 11 - A COMPARISON OF FRACTURE TOUGHNESS AND STRENGTH DATA FOR BAINITIC AND MARTENSITIC STRUCTURES. THE CURVE IS FOR SEVERAL MARTENSITIC STEELS FROM REFERENCES 9 AND 10.

Aeronautical Systems Division, AF Materials Laboratory, Metals & Ceramics Division, Wright-Patterson AFB, Ohio.
Rpt. No. ASD-TDR-63-458. PROPERTIES OF ULTRA-HIGH STRENGTH BAINITIC STRUCTURES. Final report, May 63, 29p incl illus, and tables.

Unclassified Report

The tensile properties and fracture toughness were measured in sheet material for isothermally transformed lower bainite and tempered martensite in a series of alloy steels. The major experimental variables were transformation temperature, tempering temperature, carbon content, and alloy additions. Carbon contents of 0.55 to 0.60% or higher are required to develop ultra-high strength levels in lower bainite. Lower bainite with

(over)

1. Steel
2. Bainitic Structures
3. Martensitic Structures
4. Tensile Properties
5. Fracture (Mechanics)

I. AFSC Project 7351 Task 735105
II. Contract AF 33 (657) 8426
III. Armour Research Foundation, Chicago Illinois
IV. C. R. Simcoe, J. P. Sheehan
V. Aval fr OTS
VI. In ASTIA collection

yield strengths above 220,000 psi had slightly to moderately lower fracture toughness than tempered martensite in typical low alloy steels at comparable yield strengths. At yield strengths below 220,000 psi, lower bainite was equal to or slightly better than tempered martensite in typical low alloy steels, except the 1Cr-1Mo composition which is superior to the other alloy steels studied at yield strengths up to 240,000 psi.
The fracture toughness of lower bainite is discussed in terms of transformation temperature, M_s temperature, and steel composition. A 9Ni-4Co steel developed an atypical bainitic microstructure at transformation temperatures just above the M_s temperature.

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